ARTERIAL BLOOD FLOW AND BLOOD PRESSURE MEASUREMENTS ON A PHYSICAL MODEL OF HUMAN ARTERIAL SYSTEM

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Abstract: This paper presents the results of experimental and numerical investigations of arterial blood flow and blood pressure transmitting system. The main parts of the study were the following: A)Laboratory measurements on a model arterial network, referred to as "physical model"; B)Real blood pressure measurements (BPMs) on humans; C)Numerical simulation of arterial flow. Measurements were performed on a physical model of the arterial system equipped with blood pressure measuring instrument. Blood pressure measurements were taken in laboratory circumstances: with invasive method in the artery in the shoulder of the model; and with a cuff on the model of the upper arm simultaneously. By choosing a proper material as the arm model, the measured pressure curves on the physical model showed a good accordance with the real (i.e detected during BPM on humans) experimental ones. By analyzing pressure histories -the real arterial and detected in the cuff- initial conclusions about the oscillometric method could have been drawn. Our 1D numerical code for arterial blood flow simulation purposes was validated through comparing its results with the measured arterial pressure data.

Introduction

The most frequently used diagnostic method to detect particular cardiovascular diseases is the blood pressure measurement. A possible, non-invasive tool to test and improve the measuring techniques is to examine them at a physical model of the arterial system combined with blood pressure measuring equipment. Hence the processes in the arterial network and the BPM can be detected simultaneously.

The other way to study cardiovascular processes, diseases and the effect of novel medicaments can be the mathematical description of the phenomena. In this study we present a numerical code to simulate the arterial blood flow in arterial system.

Materials and Methods

Arterial blood flow measurements: The model of the arterial system was built up using highly flexible silicone elastomer tubes with dimensions according to the geometry of the large human arteries [1]. (The whole network was fitted to a man-sized steel frame.) In the presented experiments the circulated flow was water.

The heart in our model is a membrane pump, with stroke volume and controllable frequency in the operating range of the human heart. To model the peripheral resistance adjustable clips were built in at the downstream side.

Pressure transducers were installed to the network at the following locations (see Fig. 1): directly at the heart (Aorta), at the shoulder (Arteria Axillaris) and at the thigh (Arteria Femoralis).

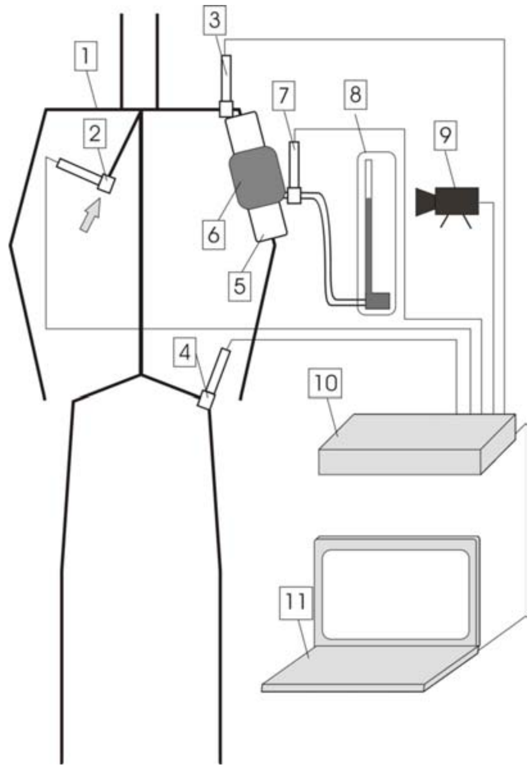

Figure 1: The measuring equipment
(1: arterial network; 2,3,4: pressure transducers; 5: arm tissue; 6: cuff; 7: pressure transducer; 8: sphygmomanometer; 9: camera; 10: data acquisition system; 11: computer;)

BPMs: The initial goal of the investigation was to develop a model, which has similar characteristics to the human body, i.e. the phenomena taking place during real BPM in the human body are in a good accordance with those in the model.

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The silicon elastomer artery in the arm had to be changed to artificial blood vessel, to approach better the real systolic and diastolic data. A special material was employed as the model of the soft tissue of the arm, which was positioned on the left upper arm of the physical model. This arm model was built up from fibre-like elements designed from fluid filled highly flexible tubes. Incompressible, but easily deformable material was needed to let the artery collapse. (In fact it is not the cuff that deforms the artery directly but the arm tissue.) The fibres were arranged around the bone (part of the steel frame) and the artery. The cuff of the blood pressure measuring equipment was fastened onto this tissue model (see Fig. 2).

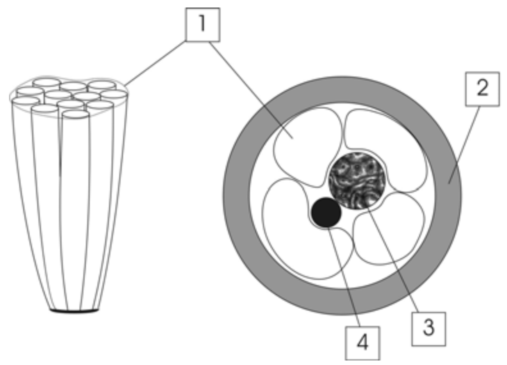

Figure 2: The upper arm model
(1: soft tissue model designed from fluid filled pipes, 2: cuff, 3: bone model, 4: artery model)

The following data were recorded simultaneously during these experiments: pressure history in the artery directly before the cuff (by pressure transmitter 3 at the shoulder); time dependent pressure of the cuff (by pressure transmitter 7); and deflection of the mercury column in the sphygmomanometer (by camera) (see Fig. 1.). Hence we could compare the real transmural pressure, the pressure in the cuff and data detected by the physiologist.

Parallel to the experiments at the model network real BPMs were taken at humans. The measurement arrangement was similar to the above described, except for the invasive way of detecting the arterial pressure.

Arterial blood flow simulations: A numerical computational model based on the method of characteristics [2] was developed in MatLab environment to simulate the arterial blood flow. This technique describes the one-dimensional unsteady flow of a slightly compressible fluid in deformable tubes. The momentum, continuity and elasticity equation – the last one describing the nonlinear elastic behaviour of the artery wall – are solved by a special technique for hyperbolic partial differential equations. Two classic nonlinear-elastic mechanical models were applied: Streeter-Wylie [2] and Mooney-Rivlin [3]. Hydrostatic relationship had to be included to the momentum equation, as it has a strong influence in the case of the „standing human" configuration.

According to the physical model, a simplified arterial pipe network was defined for the program. Furthermore, the initial conditions (at t=0) and the boundary conditions (e.g. at the bifurcations of the arteries, at the inlet and outlet) had to be formulated. The upstream boundary condition was the measured time dependent pressure in the aorta. At the ends of arteries (at the downstream side of the network) the peripheral resistance was modelled as a throttling condition.

Time dependent pressure and velocity curves at every grid point of the network can be shown by the program.

Results

Arterial blood flow: Elasticity modulus of the applied silicon elastomer pipes is one order of magnitude higher than real human arteries'. Thus measured pressure range in the arterial network has grown, it lies between 30 mmHg and 280 mmHg. (see Fig. 3)

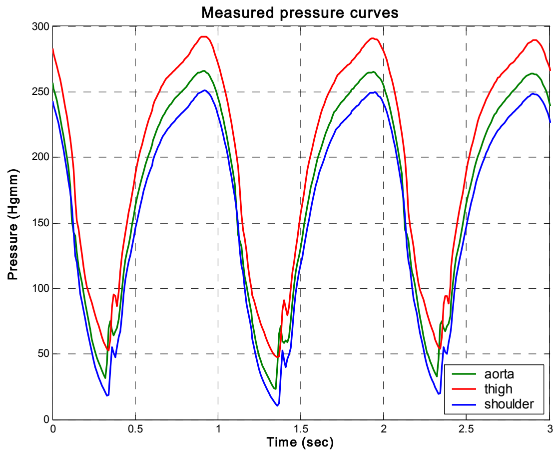

Figure 3: Measured pressure histories
(green: in the Aorta; red: at the thigh -Arteria Femoralis; blue: at the shoulder -Arteria Axillaris)

The time dependent pressure was studied by our program at locations where measurement data at the physical model were also available. Hence we could compare the measured and simulated curves. According to our former experiences a good accordance could be obtained with Mooney-Rivlin model (see Fig. 4.).

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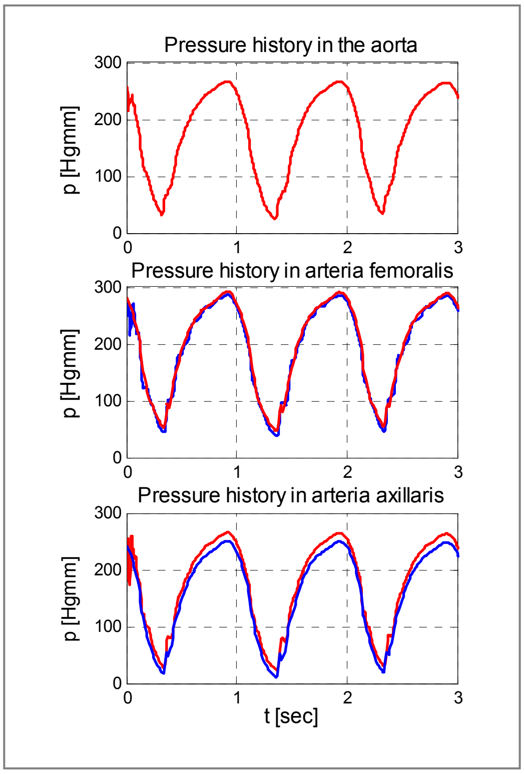

Figure 4: Measured (red) and simulated (blue) pressure curves (from above: in the Aorta, in the Arteria Femoralis and in the Arteria Axillaris)

BPMs: The core of the oscillometric BPM technique is the determination of the mean arterial BP through detecting the maximum of the cuff pressure oscillations. Thus, the accuracy of this method depends highly on the appropriate detection of this maximum point [4].

During the BPM at the model the systole was about 150 mmHg, and the diastole was about 6 mmHg. The heart rate was 60 beat/min (see Fig 5.).

As the pressure range in the model artery was wider than in a normal human artery the measurement took more time because of the accepted cuff deflation speed of 3-4 mmHg/s.

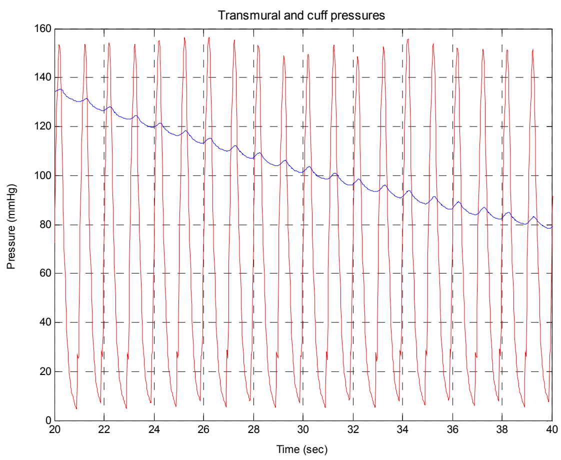

Figure 5: The arterial pressure and the cuff pressure history during BPM at the model (red: transmural pressure, blue: pressure in the cuff)

In the case of pressure curves detected on the cuff oscillations could be detected, which were similar to the real results. Using MatLab's built-in bandpass filter ('butter') with characteristic frequencies of 0.5 and 3 Hz (heart rates of 30 and 180 beat/min) the cuff oscillation history could be generated (with MatLab's built-in 'filtfilt' function) (see Fig 6. and Fig 7.).

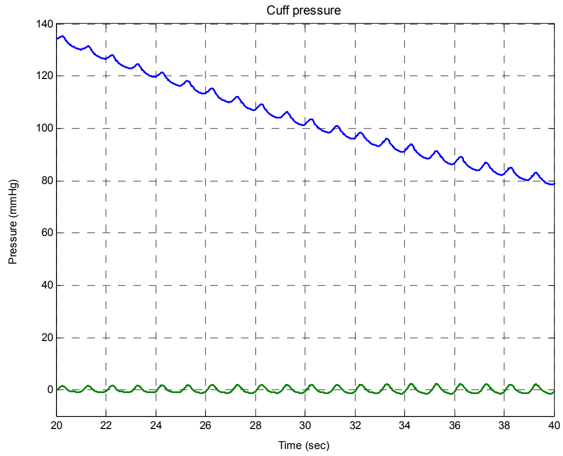

Figure 6: Model BPM – a characteristic section of the measured curve (blue: pressure in the cuff, green: cuff oscillations)

During the real BPMs the two pressure data were detected by auscultation technique. In the presented measurement the systole was about 110 mmHg, the diastole was about 70 mmHg. The heart rate was 72 beats/min.

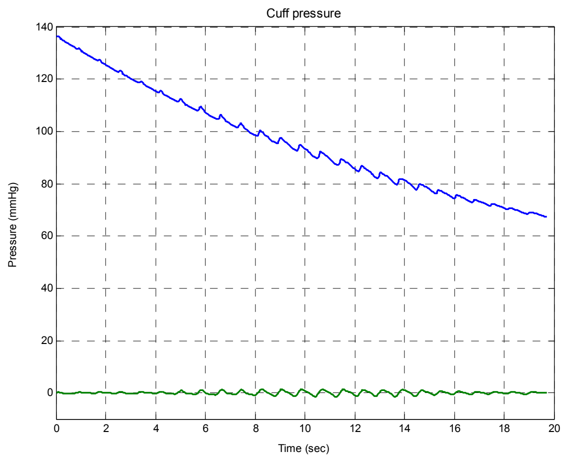

Figure 7: Real BPM (blue: pressure in the cuff, green: cuff oscillations)

In order to get the proper maximum of the oscillations the elimination of the measurement errors was necessary. It was done by using a smoothing spline [5] (see Fig. 8 and 9.). The maximum of the oscillations was approximated with the maximum point of this spline.

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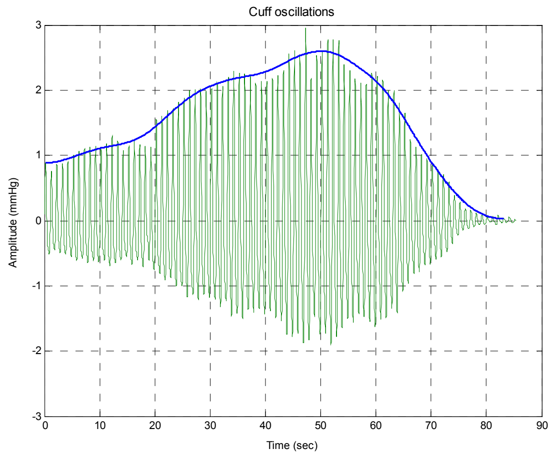

Figure 8: Cuff oscillations during model BPM (green:cuff oscillations, blue: envelope)

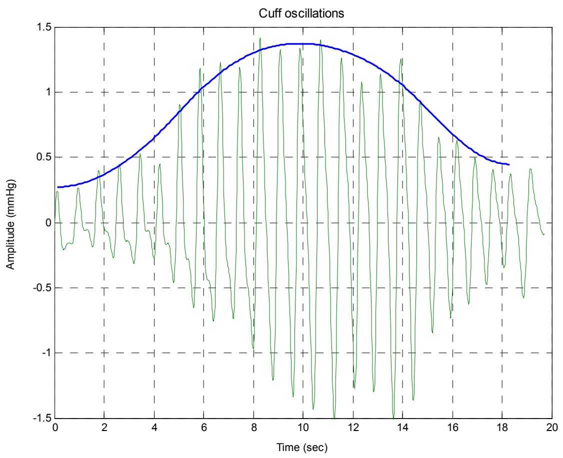

Figure 9: Cuff oscillations during real BPM (green: cuff oscillations, blue: envelope)

The mean arterial pressure was calculated as the time averaged integral of the arterial pressure wave. Thus the cuff pressure at the maximal oscillation and the mean arterial pressure values could be compared (see Fig. 10).

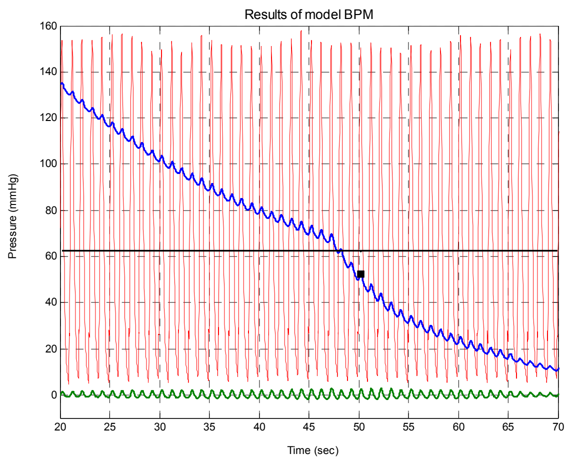

Figure 10: Results of BPM at the model (red: transmural pressure, blue: pressure in the cuff, green: cuff oscillations, black square: transmural pressure at the maximum of the oscillations, black line: mean arterial pressure)

One calculation method for the systole and diastole in oscillometric BPM is the height based approach (amplitude ratio approach). For this, the amplitude of the oscillations has to be plotted against the baseline cuff pressure (see Fig. 11. and 12.), which was generated from the cuff pressure history with MatLab's bandstop filter (with the same method and coefficients as above).

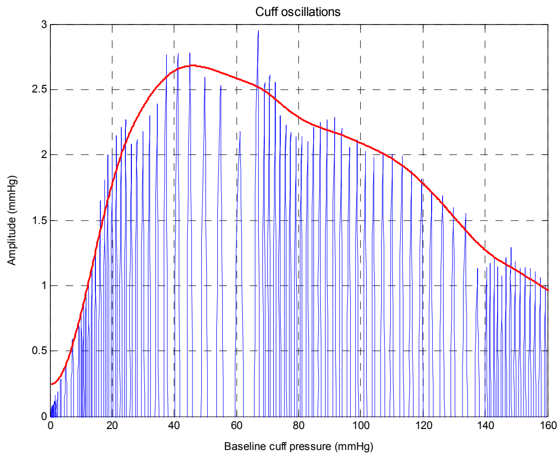

Figure 11: Cuff oscillations versus baseline cuff pressure during model BPM (blue: cuff oscillations, red: envelope)

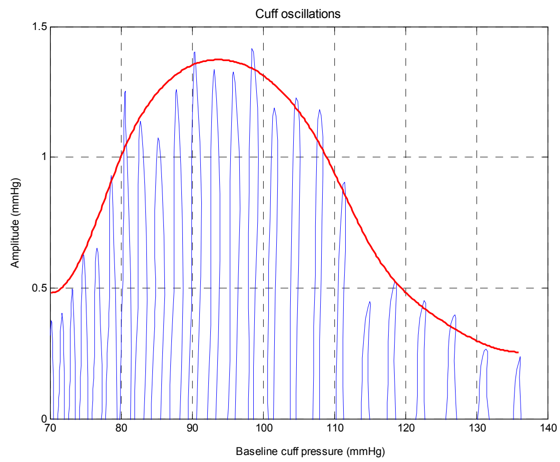

Figure 12: Cuff oscillations versus baseline cuff pressure during real BPM (blue: cuff oscillations, red: envelope)

Discussion

Arterial blood flow: Our measured and computed results showed a good accordance in arterial blood flow simulations. Although our measurements were taken at a simplified model with silicon elastomer tubes, we were able to use them to validate our program. Extending the network model to a more diversified system in the code and changing the bulk modulus to the real arteries' properties the blood flow in human vessels can be simulated.

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As every artery in the physical model will be changed to artificial vessel, our model will have better correspondence with the mechanical properties of the human arterial network.

Implementing viscoelastic artery wall properties [6] into the method of characteristics has difficulties. Accordingly a new mathematical code was developed based on finite differences method to solve the partial differential equation system describing the fluid flow in flexible tubes. Our primary model to simulate flow in one pipe is available [7].

BPM: In our results – at the model – differences were noticed between the mean arterial pressure and the cuff pressure detected at the maximum of the oscillations. In the presented experiment the mean arterial pressure was 62 mmHg while the cuff pressure detected at the maximal oscillation was 50 mmHg (see Fig. 10, black line and black square). Each of our measurements showed the coincident result: the mean arterial pressure was in average 10-12 mmHg higher.

The systole and diastole values were calculated with the height based approach too. The given range for the systolic ratio is usually from 0.4 to 0.75, for diastolic ratio from 0.6 to 0.86 [8].

At BPM on the model the cuff pressure at maximal oscillation was the mentioned 50 mmHg (see Fig. 11). The diastole calculated with the amplitude ratio approach was arisen to be between 18-28.5 mmHg (the real diastole was 6 mmHg), the systole between 107-153 mmHg (the real systole was 150 mmHg).

At real BPM the following data were calculated: diastole between 77.5 – 83 mmHg (the real diastole was 70 mmHg), and systole between 108 - 118 mmHg (the real systole was 110 mmHg), the cuff pressure at the maximum point of the oscillations was 93 mmHg (see Fig. 12). These data are summerized in Table 1.

Table 1: Measured and calculated data at model and real BPM (values in mmHg)

	Model BPM	Real BPM
Mean arterial pressure	62	-
Max. osc. cuff pressure	50	93
Systole	150 (±2)	110 (±4)
Calculated systolic range	107-153	108-118
Diastole	6 (±2)	70 (±4)
Calculated diastolic range	18-28.5	77.5-83

This means that at the model and also at the real BPM certain discrepancies can be noticed at the diastole: the diastole was under the calculated diastole range in both cases.

Coincident results could be noticed at all of the measurements (at model and also at real), although the baseline cuff pressure histories and cuff oscillation curves had different shapes.

Conclusions

We can conclude that we can model processes of the human arterial network in laboratory circumstances.

The computed numerical results – with measured data as boundary conditions – were used to validate the arterial blood flow simulations. This code is appropriate to model fluid flow in highly deformable tubes with non-linear elastic properties. In our further study we will develop a new program to simulate blood flow in arterial network with viscoelastic behaviour.

BPM laboratory model describes human arterial behaviour qualitatively well. In accordance with our results we hope to improve medical diagnostic systems and validate blood pressure measuring methods without clinical examination.

In our future study further experiments at the improved physical model are planned. Changes of the characteristic factors of the cardiovascular system (e.g.: pulse rate, arterial pressure wave form, blood pressure values, volume…etc.) affecting the BPM will be investigated.

Our model is also available for analyzing other BPM techniques. Investigation of the invasive method is being performed [9].

Furthermore a mathematical model for the dynamic behaviour of the cuff and arm tissue will be developed; also a complex mathematical model of the non-invasive BPM technique will be described.

Affiliation

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